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Artificial Intelligent Meter development based on Advanced Metering Infrastructure technology

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ABSTRACT

Smart meter is an advanced energy meter that measures energy consumption in residential, commercial and industrial facilities with additional information related to the power system. This paper aims to review system functions of the latest smart meter technology which incorporates Advanced Metering Infrastructure (AMI). The paper also proposes future smart meter with some modification and improvement of AMI technology by introducing Artificial Intelligence Metering (AIM) techniques where the energy consumed by consumers' appliances is fully supervised by AIM. The AIM function is almost the same as AMI technology, but with some enhancement including schedule of various appliance usage by customers, PV integration and power quality monitoring. These modifications can facilitate consumers to manage their energy usage wisely, meanwhile promoting green technology to the community.

Contents

1. Introduction

The development of Advanced Metering Infrastructure or AMI system has brought the greatest change in the technology of energy metering. The technology upgrades from mechanical rotating disc energy meter to electronic energy metering device and then to intelligent energy meter, called automatic meter reading (AMR) [1,2]. This technology helps send energy consumption data from buildings, factories and houses to the utilities for load curve, power quality analysis and consumers' billing purposes [3]. In the meantime, the Advanced Metering Infrastructure (AMI) is also introduced to integrate the meter with grid and households for

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better analysis of transmitted power and usage. The AMI technology includes two-way communication between utility companies and customers' smart meter [4,5]. This device communicates with consumers and utilities through power line carrier and this is aimed to help households to consume energy wisely [6]. The AMI can be defined as a 'smart meter' device due to its user-interface ability and provision of all parameters that are related with users' energy consumption as well as utility companies [7]. The parameters that are employed in AMI system are energy consumption, real power, reactive power, power factor, voltage, current, and maximum energy demand [8]. These parameters will ensure the energy usage quality at receiving end and provide information on current energy price to consumers. Moreover, most of the smart metering devices are able to record the activities of households through energy consumption profile [9,10].

Nowadays, many countries especially developed countries have implemented AMI technology in their power system. Enel SpA in Italy, BC Hydro in Canada, Oxxio Company from Netherlands and many utility companies in Europe, Australia, Japan and Korea have invested millions of dollars to install AMI devices in residential areas [11]. Several issues were reported by these companies regarding energy crisis, cyber security issues, smart meter robustness, communication signal and financial investment [12]. These issues are future challenges in order to develop a better Advanced Metering Infrastructure system. Therefore, in this paper, several ideas of AMI system improvement are proposed so as to reduce or eliminate some current issues.

The remaining part of this paper is organized as follows. Section 2 presented a review of the Advanced Metering Infrastructure system. In this section, the AMI system from the perspective of communication protocol, meter self control system, remote supervision and power consumption monitoring by consumers is presented. System software was also discussed along with data collection and encryption. In Section 3, future smart meter is proposed where Artificial Intelligent Meter model is introduced. There are three main functions of the proposed model including, home appliances scheduling, photovoltaic integration and power quality monitoring. Finally, Section 4 concludes the paper.

2. The Advanced Metering Infrastructure system

In order to deploy Advanced Metering Infrastructure system into electric distribution system, seven systems inside the smart meter need to be considered namely, system communication, system control, remote communication and monitoring, system security, remote software upgrade and data collection and encryption [13]. The following sections describe various technologies used in the aforementioned sub systems.

2.1. Communication system

Communication system in smart meter technology is a priority function since energy consumption data of consumers need to be accurately recorded in real-time or near real-time by the utility. Generally, data from smart meter will be transmitted to utility for load curve analysis and billing purposes. According to [14], integration between Demand Side Management (DSM) program and AMI system improves load management in distribution network and maximize energy efficiency. The existence of two-way communication in AMI system assists DSM program to achieve real-time pricing for billing charge. At the same time, load curve can be updated almost every minute to estimate time of maximum daily load in distribution area. With real time load curve analysis, energy price and tariff can be revised frequently so as to satisfy customers and utilities. The energy time-varying pricing can be categorized into three types which are time of use (TOU) pricing, critical peak pricing (CPP) and real time pricing (RTP) [9]. TOU pricing is less efficient compared to CPP in terms of energy price fluctuations against time. However, the most efficient energy pricing is RTP where it can be achieved whenever the AMI system is fully deployed in distribution network. The advantage of this pricing is that it reduces load demand during peak time according to consumers' concern about high bill charges. Eventually, it decreases load demand during peak time as well as excessive energy wastage.

AMI communication technologies can be divided into two approaches namely wired communication such as power line carrier (PLC) and wireless communication such as radio frequency (RF), Zigbee, Bluetooth, WiFi, WiMAX, General Packet Radio Service (GPRS) etc. The wireless protocols are selected based on five factors namely good transmittable range, high security, good bandwidth and quality data transmission as well as least latency [12]. The radius of network coverage for wireless communication protocol is varied upon power transmission and frequency. Generally, high frequency requires more power to be transmitted yet its radius is smaller when compared to low frequency. From the literature review, the wired communication specifically the PLC is the most suitable and applicable protocol by many companies since data is only transmitted through existing power cables or grid network [12]. Khalifa et al. [15] surveys four communication protocols available for AMR device and one of them is PLC. The authors highlighted frequency selection, propagation speed and distance as main specifications for PLC implementation. Since the data travels through voltage signal, the voltage level carried is also considered. Although PLC provides low maintenance cost and has good efficiency, it suffers from limited bandwidth and difficulty in supporting large scale network [15]. In that case, integrating several communication protocols with PLC might overcome its drawbacks such as WiFi, Micro-power Wireless, Optical Fiber etc. [16,17]. Instead of communicating through power cables, wireless communication technology is an alternative data transmission medium between households and utility. There are seven reliability aspects for both communication protocols which are type of network, range of network, quality of signal, cost of network devices, cyber security, terrestrial difficulties and availability of signal [12]. The future prediction of communication traffic is another consideration as signal congestion occurs due to same bandwidth between communication signals. This can cause signal interference in the network and data might be interrupted during transmission [18]. Therefore, selection of signal protocol is critical to ensure the data is not corrupted when transferring, due to noises and interferences from other communication signals. Table 1 shows different communication protocols and their parameters which can serve as guide when integrating a particular type of protocol for the smart meter application.

2.2. Control system

The control system is one of the built-in systems in smart meter devices where it functions as self-monitoring and controlling consumers' utilities. For example, Cao et al. [19] conducted an experiment for water flowing system controlled by AMR meter. Water sensors located at the main pipe measure the water flow velocity and transmit it to AMR meter to record and monitor. A proposed error estimation algorithm is programmed into AMR system device as a feedback component to water flow activity. In general, the function of feedback system in the meter device as illustrated in Fig. 1 is to calibrate output values by controlling input values in smart metering system. Normally, external and internal noises in practical operation interrupt the system which frequently

Table 1
Properties of Zigbee, GPRS/GSM, Wi-Fi, Bluetooth and PLC communication protocols.

Technical parameter	Zigbee	GPRS/GSM	Wi-Fi	Bluetooth	PLC
Standard	IEEE.802.15.4		IEEE.802.11	IEEE.802.15/1	
Network topology	Mesh Tree Star	Tree	Star	Star	Tree
Work frequency (MHz)	2400/868/915	800–1900	2400–5800	2400	3–148 kHz
Transmission range (m)	10–70	Mobile N/W	10–100	10	300
Transmission speed (kbps)	20–250	56–114	11–105 Mbps	723	4–128
Network content	255/65,000	N/A	32	8	Hundreds
Battery life	Longer	Shorter	Short	Long	Wired
System consumption	Lower	Low	High	Higher	N/A
Cost	Lowest	Higher	High	Lower	low

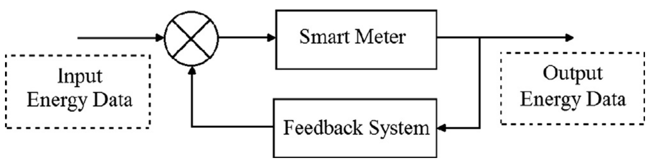

Fig. 1. Feedback in smart meter system.

causes slight deviation in output values. Therefore, the feedback system readjusts the input rate so that the output rate lies within an acceptable range. For example, to maintain power factor above 0.85, Ali et al. [20] suggested remote switch to external capacitor bank. The relay switch must be controlled under smart meter supervision. The smart meter measures the reactive power to decide the quantity of capacitor to connect parallel to load. As a result, it prevents penalty charge by utility since power is consumed efficiently. Instead of controlling utility buildings, Neal [21] presented benefits of AMI applications to utility companies. The author manipulated AMI system as 'Voltage Sensors' to propose Advanced Volt/VAr Control (AVVC) system. The function of 'Voltage Sensors' is to send voltage information to AVVC via central Meter Data Management System (MDMS). After that, Smart Inverter in AVVC system recovers voltage drop and mitigate reactive power flow instantaneously based on data analysis from AVVC system. This system maintains the voltage and minimizes reactive power flow in distribution network.

Recently, unbalanced voltage and current problems have become a common issue in the field of power system control. The unbalanced issues are due to load capacity differences between households as it depends on quantity and appliances used in each facility. Unbalanced load can affect excessive residual current in neutral line [22]. In order to reduce residual current, Pasdar et al. [8] proposed intelligent three phase balancing load by redistributing single phase residential loads equally between three phases via smart meter to solve this problem. In this research, smart meters play the role of sending four data including, reactive power, active power, voltage and current to host unit for load balance analysis. Ant Colony Optimization (ACO) is used as a three-phase current balancing algorithm in the host unit. In consequence, relay contact toggles the line current according to host unit decision in order to balance load between three phases. This application optimizes power transmission in distribution network via smart metering. Another issue regarding energy waste is standby power mode in electronic appliances. According to International Energy Agencies, 10% of total energy waste comes from standby mode option from televisions, laptops, Personal Computers (PCs) etc. As a solution, Heo et al. [23] presented Host–Agent control mechanism to eliminate standby power mode. There are four primary objectives of Host–Agent control which are to realize home automation based control, reduce standby power mode for all household appliances below 203 mW, embed sensors into all devices, provide low power mechanism and high reliability. The Host is a main system that controls all Agents activities located either in socket outlets or embedded in electronic appliances. Although the results indicated high contribution in effective energy management, the research was not associated with smart meter development. Thus, further study is required to integrate this mechanism into smart meter system.

2.3. Remote communication and monitoring

The remote communication system is developed based on relay mechanism controlled from utility base station. The utility is authorized to remotely connect or disconnect the electricity via smart meter depending on the households' electricity bill payment issues [24]. Furthermore, monitoring system from base station serves as an evidence record to tampering and hacking activities by irresponsible users. However, Cleveland [25] questioned the reliability of remote disconnect/connect function in metering system when undetected hacking and tampering issues are encountered. The author stated the possibility of meter to send 'invisible' signal to disconnect millions of meters instantaneously by hackers. Thus, it highlighted four generic criteria for security assessment which are confidentiality, integrity, availability and accountability. These criteria are applied into AMI network to strengthen the robustness of security system.

2.4. Security system

The security system is the toughest system to build in a smart meter system. Many cases related to electricity theft occur because meters fail to detect physical and system modification. Even though the robustness level of security system is improving year by year, techniques to manipulate the meter might be easily exposed on the internet. Ideas and knowledge on meter development are shared through the World Wide Web by engineers, programmers or hackers as free and public information. However, this information could be abused by anonymous consumers to corrupt the meter system. As previously mentioned, four requirements are crucial for robust security [25]. The first criterion is confidentiality of consumers' energy usage. An agreement must be signed by both utility and consumers which classifies energy data information from any persons or organizations or companies except with authorized permission. The second criterion is Integrity security which can be divided into smart meter integrity and integrity of customer gateways. The meter must be intelligent to protect from unidentified alterations and the customer gateways must be able to sense unauthorized changes. Next criterion is continuous availability between smart meter and AMI system and finally, accountability or non-repudiation for transparent billing process and control commands.

Many researchers proposed communication security approach for meter security system. For example, Chen et al. [26] presented a second generation Zigbee protocol for signal security where

database architecture of Zigbee consists of high and complex requirements to access data. An additional Zigbee Device Object (ZDO) layer has been added in the latest Zigbee architecture to generate security relationship between nearby meters [27]. Therefore, any false signals can be recognized through comparing meter identifications between neighbors' and householders' meters. This technique enhances data security and originality.

2.5. Remote software upgrade

Most microprocessors inside smart meters require operating system to execute metering infrastructure. Basically, any software installed into the microprocessor will operate according to its program. For smart meter software, the common programs are measuring active and reactive energy, voltages and demand profile parameters in every time interval for load profiling [28]. Sometimes, several adjustments on the software programs are required to improve measurement accuracy as presented by Luan et al. [29]. They improved the reliability indices accuracy and introduced customer interruption cost in AMI system. The refinement of the proposed reliability calculation is based on detailed consumers' load and outage event which only can be obtained through a smart meter. Furthermore, an additional customer interruption cost data can be used by utility to estimate cost of loss due to a power failure event. So, the software should be updated or upgraded to improve functionality of AMI system. Yao-Chung et al. [30] proposed machine-to-machine (M2M) remote software update using Dynamic Software Update Model (DSUM) technique. This technique eliminates the need for rebooting after software is updated. Usually, rebooting is a common procedure for any software to execute the updated system. However, previous runtime states will be lost after reboot and it is not convenient for non-stop running processes required in some systems such as energy metering systems. Therefore, this application can be developed in smart meter since it preserves runtime states, which means data interruptions can be prevented when meter software is being updated. As a result, this approach increases company management level since it reduces labor cost and time to manually upgrade smart meter at each facility.

In [28], the authors have presented their own software program, called "AMI Configuration and Data Collection system" installed in data processing center at smart meter base station. Three functions of this software are receiving, decoding and saving data into database for future analysis such as energy pricing or load profiling analysis. Sometimes, unusual data records could be corrupted data due to sudden interruption or shut down conditions due to short circuit or lightning strike. This software only records energy data without considering corrupted data as mentioned above. In consequence, energy consumption data becomes less accurate and it will affect load profile analysis. Seoung-Hwan et al. [31] overcame this problem with Outage Management System (OMS) where the system identifies outages locations and recovers them immediately. Then, Chen et al. [32] introduced several techniques such as nonparametric regression, *B-spline* smoothing and *Kernel* smoothing techniques to extinguish corrupted data in load profile. Both techniques can be upgraded into AMI system so that database records contain error free data. Therefore, the enhancement of software can be made easily by utility.

2.6. Data collection and encryption

Before the smart meter was invented, energy data were collected manually by workers for billing purpose. This conventional method was applied for mechanical rotating disc energy meter as it only displays energy consumption in kW h [12]. Smart meters, on the other hand, measure, record and send energy data in real time or near real time. Another issue that needs to be addressed is, when a lot of energy data from smart meters are transmitted to the same central station, it could be difficult for utility provider to manage the billing for each house. In order to simplify the management process, the collected energy data are encrypted with house identification.

Popa [33] suggested a method for energy data identification. The author has introduced a Meter Interface (MI) system that operates similar to smart meter. It transmits energy data with encrypted data of meter identification to gateway located at utility central station. The gateway addresses the MI by using algorithm in C programming language. All MI identifications will be memorized by gateways. This method facilitates utility in billing management. Another latest research development on data encryption is homomorphic encryption [34]. Previously, Public Key Cryptosystem is the most commonly used data encryption technique. The encrypted keys are generated by some complicated mathematical properties such as discrete logarithm, integer factorization and so on, without initial identification of secret key where the decryption technique is already exposed through various online resources. In homomorphic encryption however, all data must be encrypted and decrypted by one isolated sub-system called PKC-HE. The sub-system separates energy data encryption into two different network levels which are H-net and L-net. L-net network exists between customers and utilities while H-net network only communicates between Generation, Transmission and Distribution Companies. The purpose of this isolation is to block any unidentified signal breach into another network by encrypting key identification according to network area. However, data encryption technique is almost the same as Public Key Cryptosystem. Therefore, any data transmitted can still be read by unauthorized person.

2.7. Other development of AMI

From the economical point of view, millions of dollars have been invested through the involvement of many utility companies such as power, water and gas providers to deploy metering infrastructure in residential, commercial and industries buildings. Hongfei et al. [35] proved that water management system can be incorporated with smart metering system under AMR device. The authors proposed predictive usage analytic toolkit to analyze water usage in customers' residences. This research indicates that both water and electricity management system can be managed by the same meter device and same base station. So, the cooperation between these utility companies including water and gas providers under smart meter development will merge all utility companies into one big company. The impact of merging may eradicate dependency on the government and strengthen companies' financial statuses. Thus, utility billing is not only electricity payment but also consists water and gas payment in the same bill [36].

Other than that, the prepayment system applied by some utility companies is an alternative billing scheme to raise consumer consciousness about energy waste and carbon emission [37,38]. In several countries such as Brazil, Congo, Namibia and South Africa, the prepayment system is selected as electricity payment since it increases 20% of companies' revenue compared to post payment billing system [39]. The prepayment system is applicable in certain countries because of their geographical factor, in particular, unaddressed and scattered settlements. However, it is impractical to be applied in developed countries due to high population density and lots of consumers are exposed to illegal education from internet to produce token fraud of prepaid energy meter [40].

In 2008, Saab Grintek firm received a contract from the Indian government to install 500,000 units of prepaid smart meter in order to curb energy crisis in India [41]. The meters installed are different than the usual prepayment meters because they offer customers billing payment choices to either stay on prepayment option or change to post payment billing. Then, utility base station will switch remotely through smart meter communication system. Combining consumer-oriented interface meter proposed by Benzi et al. [42] and Saab Grintek smart meter facilitates households to opt for a suitable payment mode according to their manageability.

3. Future smart meter

When defining 'smart' terminology, the device should support multiple programs instead of only displaying kilo Watt hour (kW h). The ability to integrate with many software programs and external hardware is critical as it does not only provide more information to consumers but must also be able to adapt to consumers' desires. This terminology has been described in mobile phone technology where it defined a smart phone as a portable telecommunication device, operated by a powerful processor, requires an operating system to process all software applications installed, and has an intelligent user interface [43]. Moreover, internet accessibility and Global Positioning System (GPS) are the priority requirements to make smart phone more intelligent. Another example for 'smart' terminology is smart TV. It has some similar features as smart phones which is intelligent user interface and web accessibility [44]. Benzi et al. [42] presented the benefit of smart meter interfacing when it is fully integrated with all in-house appliances and user-friendly to householders. The objectives of future home automation is to aim for energy saving and carbon emission reduction. The authors proposed four architectures of smart meter network for consumer-oriented meter house interface including, dedicated serial line, wireless, power line and web-based communication so as to comprehend and facilitate customers into wise electricity usage. Therefore, in order to fulfill 'smart' criteria for smart energy meter, intelligent user interface, internet accessibility and integration ability to other devices will be required.

3.1. *Artificial Intelligent Meter (AIM)*

In the future, Artificial Intelligent Meter (AIM) or AI meter will be the main choice for smart meters since it manages energy consumption of consumer independently, communicates with the households and providers and improves quality of power supply under supervision of artificial-intelligent power quality diagnosis in AIM device [45]. All appliances in the house will be monitored and controlled by AIM after it receives householders' permissions. The AI meter recognizes all appliances location based on Smart Multi-Power Tap (SMPT) device approach [46]. The SMPT is a mini-outlet device that detects power flow from any active socket outlet. Each active socket outlet will send its identity and location to AI meter via Home Area Network (HAN) for monitoring and data records. The ability of SMPT to switch off appliances remotely after it received command from the meter assists AI meter to manage all appliance activities under households' permission. Moreover, the SMPT placement will be supported by RECognition of electrical Application and Profiling in real-time or RECAP combined with Artificial Neural Network (ANN) process [47]. The RECAP technique profiles all appliances' load separately by assigning appliances based on its power consumption, power factor value, peak current and voltage, RMS current and voltage, signature length, and sampling frequency. Meanwhile, the ANN process will be trained to identify and classify all appliances signatures

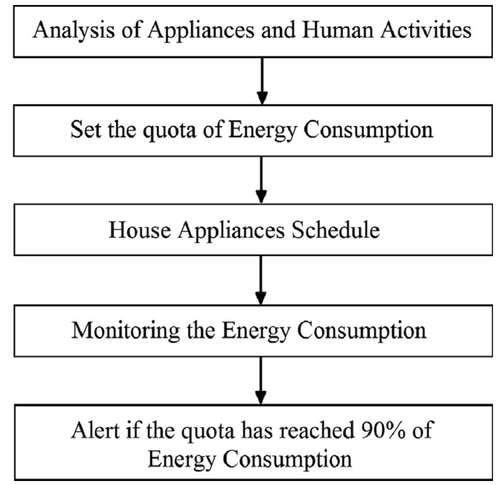

Fig. 2. AI meter operation in flow chart.

according to level of energy consumption. An additional feature in AI meter is short-term load forecasting [48]. This feature predicts future load profile pattern based on statistical analysis from previous load profile at certain evaluation period. With this feature, the AI meter will recommend a suitable schedule for all appliances usage to householders. The schedule must be synchronized with human presence of in the house. Therefore, broadcasting wave must be employed in SMPT to detect the human presence and absence in the house [49].

The advantages of AI meter include controls of the energy consumption efficiently since it provides a quota of energy consumption to customer. The energy quota is a reference for AI meter to manage all appliances use in customer's premises. Fig. 2 indicates the AI meter operation as a flow chart and the explanations are as below:

1) The meter will analyze and record human activities in the house and power consumed from each appliance by calculating the average energy consumed for a day, week and month and differentiates between weekdays and weekends. These two factors are important and taken into consideration to determine the energy quota for householder.
2) The AI meter will categorize all appliances into three groups which are light loads, medium loads and heavy loads. These groups are based on the capacity of load and the frequency of appliance use.
3) The AI meter will suggest the range of energy quota to customers to decide the quota setting of energy consumption. After the quota of energy consumption is set, the AI meter will suggest several options of schedule for appliance use. The schedules are personalized to customers' activities in their houses.
4) If the energy consumption has reached 90% of the quota, the AI meter will alert the householders by sending this information to householders' mobile phone or e-mail.

3.2. *Photovoltaic (PV) integration*

In the next decade, photovoltaic or PV installation on every rooftop could be a reality. The AI meter will play its role as a management system between energy generated by PV and energy supplied from grid [50]. The system may reduce the energy supply from grid since PV can provide parts of energy to lights and medium loads such as fluorescent lamps, motors etc. Furthermore, the energy generated by PV will also be stored into batteries

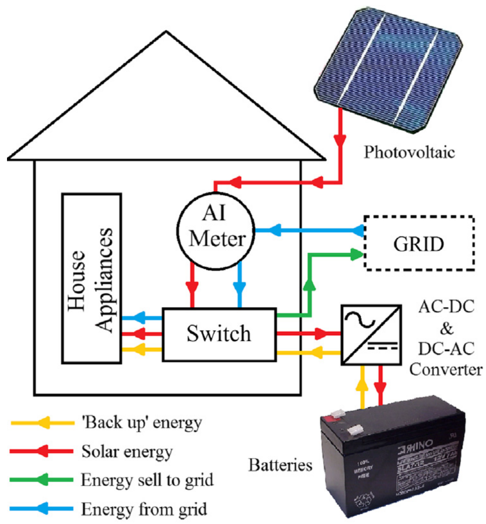

Fig. 3. AI meter operation.

located in the house and applied as 'back up' energy during outages. An additional switch located in the house's distribution board will be controlled by the AI meter so as to switch between grid power supply and batteries during power outage. The ability of AI meter to sense instantaneous over-current circumstances before the circuit breaker and switch to batteries will be a solution to preserve the house appliances from any disruption. Moreover, an excess energy generated by PV will be sold to grid where the AI meter will measure the energy transferred to grid. This condition can reduce the electricity bill since it can deduct the energy purchased from utility. Fig. 3 illustrates how the AI meter works with PV integration.

3.3. Intelligent power quality meter

Another function in AI meter is power quality monitoring that focuses on Total Harmonic Distortion (THD) detection. De Capua [51] has introduced 'grey box' calibration in Fast Fourier Transform calculation by using Field Programming Gate Array (FPGA) platform. This feature will be implemented into the AI meter. The accurate measurement will determine the percentage of distortion generated by harmonic source. This energy meter not only measures the percentage of THD, but it also can include the penalty charge for high harmonic distortion especially current harmonics. Referring to British Standard Regulation, BS EN 50160, the total harmonic distortion percentage for voltages must not exceed 8% for one week monitoring in low voltage distribution network and the penalty charge will be issued if the consumers violate the regulation. The meter will alert the customers and the penalty charge will be included in the monthly bill statement. With the assistance of the AI meter, the THD monitoring can be operated all the time. Therefore, harmonic monitoring is necessary at an earlier stage to ensure good power quality [52].

4. Conclusion

This paper reviewed several systems inside the Advanced Metering Infrastructure which are system communication, system control, remote communication and monitoring, system security, remote software upgrade and data collection and encryption. All these systems are required in order to fulfill the 'smart' criteria. A new modification of Advanced Metering Infrastructure (AMI) technology that is the Artificial Intelligent Meter (AIM) is proposed in this paper to enhance the reliability of the smart meter, increase the power quality in distribution area and promote green technology to consumers.

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